COMETS

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ABSTRACT

Over the 1-2 years since the last major reviews of this topic, IUE has been used to study several additional comets including the first dynamically new comet to approach closer than 3 AU. Thus for the first time, we can begin to draw some conclusions about the differences between old and new comets. This review emphasizes the results relevant to the nature of cometary nuclei.

Keywords: comets, spectroscopy, chemical composition, cometary nuclei.

1. INTRODUCTION

One of the primary goals of cometary astronomy is to determine the physical structure and chemical composition of the usually undetectable cometary nucleus because it is commonly accepted that knowledge of nuclei will place important constraints on the conditions in the proto-solar nebula when the planets were formed. With only a handful of exceptions, our knowledge of cometary nuclei is based entirely on observations of the gas and dust in the coma, a task for which IUE is extremely well suited because its spectrometers cover the principal resonance lines of several molecular species as well as of most of the cosmically abundant atomic species.

The step from measuring these species in the coma to estimating the composition and structure of the nucleus is, not surprisingly, a rather difficult one which requires that we fully understand a wide variety of relevant physical processes which occur in the coma. Despite the series of spacecraft encounters with comets Giacobini-Zinner and Halley, our understanding of these processes is well-developed in only a few areas. Observations with IUE have also played a key role in understanding these processes.

Recent reviews of the IUE observations of comets by Festou and Feldman (Refs. 1, 2) have summarized the results through the preliminary analyses of the observations of Comet Halley. For this review on the tenth anniversary of IUE, one might dwell primarily on a complete review of what has been learned in those ten years. Because the two previously cited reviews covered the earlier advances so well, we can emphasize the more recent results although the context will be discussed. One might expect that the additional year or two of observations and analysis would not have led to significant advances over the previous 8 to 9 years but this is clearly not the case both because some particularly interesting comets were available in the last two years and because our understanding of the observations of Halley is continually improving.

Observations of comets are notorioulsy difficult under any circumstances and with IUE some of these complications are exaggerated even more. These include the need to observe at the smallest elongations possible, frequently involving discharging the spacecraft batteries in recent years, the fact that often a comet must be observed very soon after it is discovered and before its orbit is well known, the fact that comets sometimes move much faster than any other target observed with IUE, and potentially the most difficult, the fact that all interested scientists must get their observations at the same time. These difficulties have all been overcome with remarkable success due to the outstanding performance of the telescope operators and resident astronomers and to a remarkable degree of cooperation among the interested scientists. This has allowed, e.g., blind offsets on a very rapidly moving comet, many-hour exposures on a comet moving at more than an arcsecond per second of time at non-uniform rates, several 12-hour exposures combining Vilspa and Goddard shifts, and the ability to observe comets within days of their discovery.

2. SCOPE OF THE OBSERVATIONS

The previous reviews (Refs. 1, 2) listed 26 comets observed with IUE through mid-1986 of which only one, P/Encke had been observed at more than one apparition. The total number of comets observed has now increased to 32, of which P/Encke has now been observed at a third apparition and P/Borrelly at a second apparition. These additional observations are important for two reasons. The repeated observations of the same comet at successive apparitions allow us to determine which aspects of the comet's behavior are regular and repeatable and which might be transient phenomena, historically one of the more challenging aspects of cometary astronomy. Over a sufficiently long interval one

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Table 1.

A. Types of Comets Observed

Dynamical Type	Total Number	Multiple Apparitions	Well Studied
Short period P < 200 y	17	2	4
Long period P > 200 y $(1/a)_0 > 10^{-4}$ AU^{-1}	9	-	3
New $(1/a)_0 < 10^{-4}$ AU^{-1}	1	-	1
Uncertain	3	-	-

B. Well Studied Comets

Type	Name	q [AU]	Time Interval	Heliocentric Distance pre- [AU]	Heliocentric Distance post-
LP	Bradfield 1979 X	0.55	80/01/10-80/03/03	---	.71 - 1.70
LP	Austin 1982 VI	0.65	82/07/11-82/11/07	1.10 - 0.81	---
SP	P/Giacobini-Zinner 1985 XIII	1.03	85/06/22-85/09/11	1.44 - 1.03	1.03 - 1.13
SP	P/Halley 1986 III	0.59	85/09/12-86/07/08	2.59 - 1.01	0.84 - 2.53
N	Wilson 1986ℓ	1.20	86/09/05-87/11/07	3.31 - 1.20	1.20 - 1.42
LP	Bradfield 1987s	0.87	87/11/27-	1.44 - 0.90	0.95 - 1.15
SP	P/Encke 1980 XI 1984 VI 1987-	0.34	80/10/24-80/11/05 84/04/24-84/05/12 87/08/15	1.01 - 0.81	0.75 - 1.06
SP	P/Borrelly 1980 X 1987p	1.36	81/02/06 87/10/26	1.38 - 1.36	1.36 - ?

can also look for secular trends in the behavior of periodic comets but ten years is far too short a baseline for that. The observation of additional, previously unobserved comets is important also in order to understand the distribution of cometary properties over the ensemble of all comets.

Table 1A lists the observations that have been made as a function of the dynamical history of the comet. The new comets are those that are entering the inner solar system for the first time from the Oort cloud, presumably due to a recent perturbation by a passing star. They have essentially zero binding energy as expressed by the reciprocal semi-major axis prior to planetary perturbations, $(1/a)_0$. These cometary nuclei should exhibit the original surface produced when the comet formed, modified only by 4.5 billion years of exposure to cosmic rays. Successive passages through the inner solar system, with the accompanying planetary perturbations, lead in a random walk either to more tightly bound orbits or to ejection from the solar system. They also lead to release of volatiles from successively deeper layers in the nucleus. The short-period comets, which are most tightly bound to the sun and somewhat arbitrarily divided from the long-period comets, are, at least statistically, releasing gases from what were originally the deepest layers in the nucleus, perhaps through a relatively inert mantle developed on previous perihelion passages. It is therefore important to understand whether or not there are significant differences in composition or other behavior with dynamical age. The comets listed as well studied are those that were observed at four or more different points in their orbit covering a significant range of heliocentric distance and/or time. These comets are listed individually in Table 1B and represent the only comets for which we have enough data to make useful statements about the variation with time and/or heliocentric distance. Most of the other comets were observed only during a single shift either to investigate particular physical problems or to improve our knowledge of the distribution of compositions.

The table gives the type of comet, the identification, the perihelion distance, the time interval of the observations, and the range of heliocentric distances both pre- and post-perihelion. For many reasons P/Halley was the best studied although the results from Comet Wilson are at least as interesting. These two comets were comparably bright and comparably deep exposures were obtained on both, exposures up to 12 hours. Because most of the comets have low surface brightness, the bulk of the observations have been made at low dispersion and, with only one exception, all the high-dispersion exposures have been on the comets listed in Table 1B as well studied. Similarly with very few exceptions, it is only the comets in Table 1B for which exposures were made at any position other than centered on the photocenter.

The result of this pattern of observations is that there is a handful of comets on which we have made observations diagnostic of physical processes and which can tell us directly about the chemical abundances. For another two dozen comets we have a "snapshot" or two which can be used, together with the models derived from the well observed comets, to estimate the chemical compositon at a

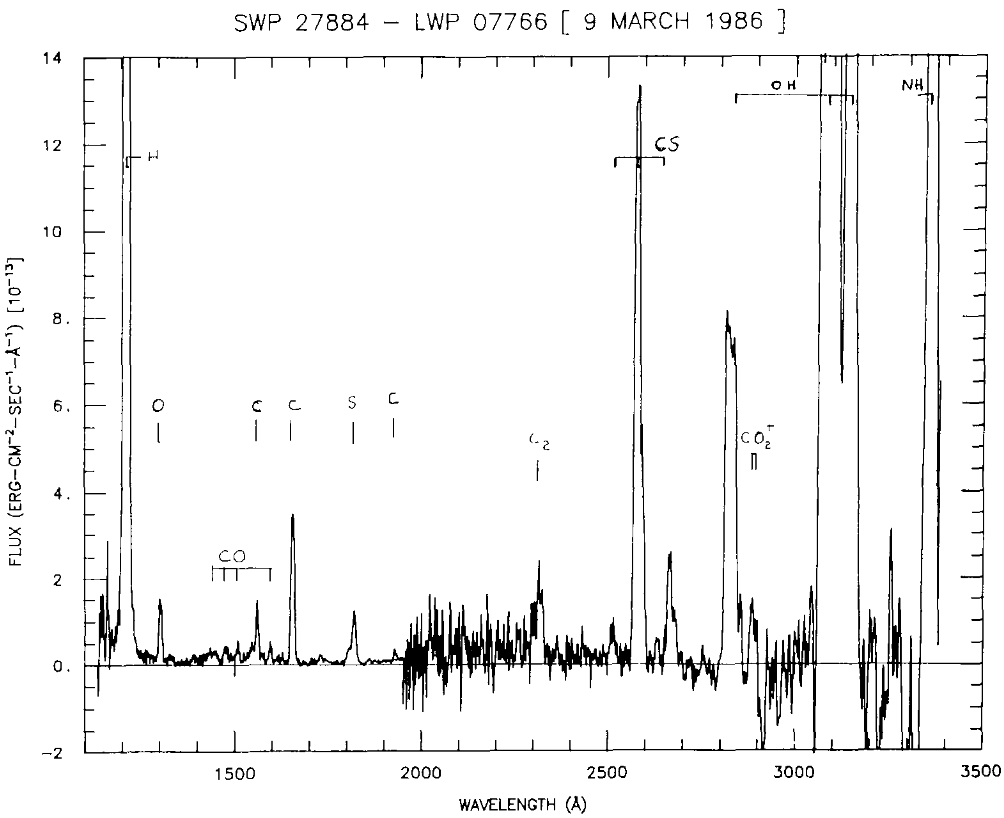

Figure 1. Composite spectrum of P/Halley on 1986 March 9. The OH bands were saturated and the continuum between 2800 – 3000 Å were overexposed in the non-linear region of the ITF.

particular moment and thereby approach the question of the distribution of abundances among comets. These data can also be used as an ensemble to study the variation of abundances with heliocentric distance. Because of space limitations, this review will emphasize the empirical nature of comets while omitting many of the recent advances in understanding physical processes such as excitation mechanism, dissociation/ionization processes, and so on. For that reason, this review is selective rather than comprehensive.

3. IDENTIFICATION OF NEW SPECIES

Qualitatively low dispersion spectra of most comets look very similar (Ref. 21) and Figure 1 shows a typical recent composite spectrum from both LWP and SWP cameras. Many of the identified species were identified prior to the launch of IUE in rocket spectra of Comet West 1976 VI (Refs. 3,4) although the IUE data have allowed the definitive identification of several species of major importance.

As discussed in earlier reviews, the Mulliken bands of C_2 at λ2320 were first positively identified in IUE spectra of comet Bradfield 1979X (Ref. 5) as was the ^1S-^3P transition of [OI] at λ2972 (Ref. 6). Although these features had not been previously observed, their existence could have been predicted from the existence of spectral features of the same species at optical wavelength. Similarly, bands of OH^+ have been identified (Ref. 7).

The next new identification came in 1983 with the remarkably close (0.03 AU) passage of comet IRAS-Araki-Alcock 1983 VII. At the time of closest approach, S_2 was the second most prominent emitter, second only to OH, in the LWR spectrum as shown in Figure 2 (Ref. 8). It is extremely unlikely that

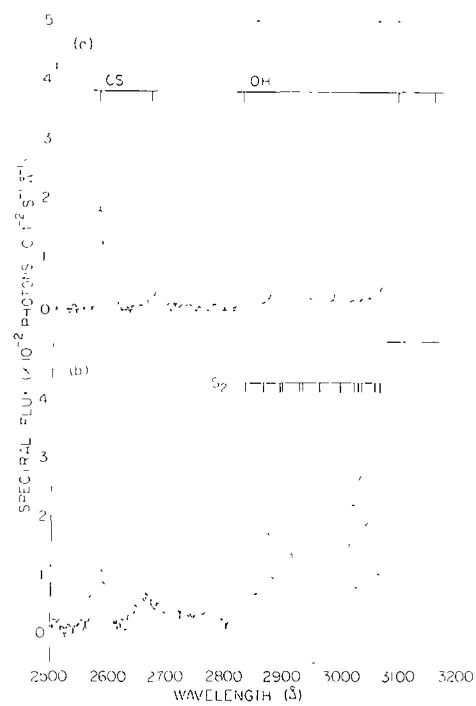

Figure 2. Spectra of C/IRAS-Araki-Alcock b) centered on the nucleus and c) offset by one slit length from the nucleus. The S_2 is visible only within a few hundred km of the nucleus.

this species could have been predicted since it is extremely unstable and has still never been convincingly detected in any other celestial source. Furthermore, it was only the existence of an outburst by the comet at the time of closest approach coupled with the remarkable spatial scale (25 km/arcsec) which made the detection possible although Wallis and Krishna-Swamy (Ref. 9) have suggested that S_2 is weakly present in the spectra of several other comts. The existence of this species, presumably in all comets despite the lack of other convincing detections, has been used to argue that the cometary ices were never very warm after their formation as the mantles of interstellar grains (Ref. 10).

Experimental work by different groups (Refs. 11, 12) has not only raised somewhat the estimate of the highest temperature to which the ices could have been heated but also shown, as was expected, that other sulfur-bearing species should be present, particularly SO and SO_2, if the proposed scenario for formation of S_2 is correct. Wallis and Krishna-Swamy (Ref. 9) have argued that SO is present, e.g., in the IUE spectra of comet IRAS-Araki-Alcock. This is certainly the best comet in which to search for SO since SO should appear close to the nucleus and should therefore be most visible in the comet that was closest to Earth. In an attempt to further test this important identification, Kim (private communication) has calculated theoretical fluorescence spectra of SO in order to predict more accurately the shape, position, and relative intensities of the SO bands. Figure 3 compares that calculated spectrum with an observed spectrum of comet IRAS-Araki-Alcock from which the reflected solar continuum has been removed by fitting at longer wavelengths. We believe that the fitted spectrum of SO corresponds to roughly a 1-σ upper limit since the profiles do not match the peaks in the oberved spectrum. The column density of SO which would produce a spectrum of this intensity corresponds to a production rate roughly an order of magnitude greater than that of S_2 in the same comet. This is certainly a plausible result in terms of the ratio of S_2 to SO seen in the laboratory experiments but it runs into difficulty with the total amount of S since S_2 and CS can account roughly for both the total cosmic abundance of S expected in comets and the observed emission

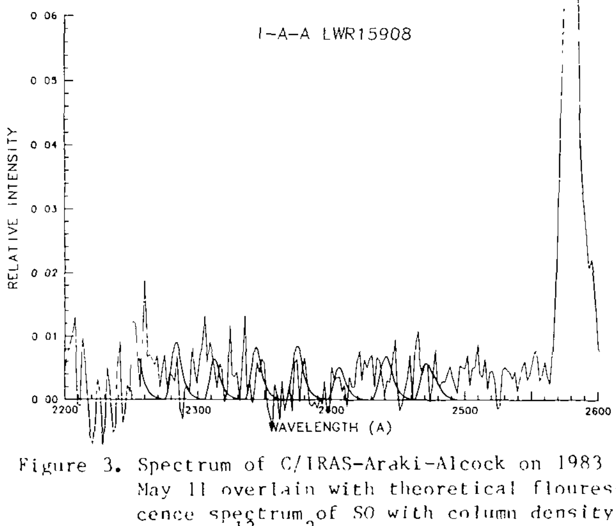

Figure 3. Spectrum of C/IRAS-Araki-Alcock on 1983 May 11 overlain with theoretical flourescence spectrum of SO with column density 3.5×10^{13} cm^{-2}. A 3-σ upper limit would be roughly a factor 3 higher.

by atomic S in comets (but see next paragraph). Although these results are uncertain by a factor two, an order of magnitude higher abundance would be difficult, although probably not impossible, to reconcile with these data. It is clear that the search for other sulfur bearing compounds, specifically SO, SO_2, and H_2S, is an extremely important one since the presence or absence of these compounds at abundances comparable to that of S_2 is critical in assessing whether or not our hypothesis for the source of S_2 is correct. Although the work of Wallis and Krishna-Swamy (Ref. 9) is an important stimulant, a definitive identification and determination of the abundances of these species, will require an order of magnitude improvement in signal-to-noise ratio compared to data reduced and presented to date.

The most recent identification is of the S I triplets at λλ1425 and 1474 by Roettger et al. (Ref. 13) in Comet Wilson 1986ℓ. Although the S I triplet at λ1814 has been known for some time, these other multiplets had not been previously reported and were discovered here primarily because the emission at λ1474 is pumped by a solar emission line and is thus strong only at heliocentric velocities near 0, a situation which normally occurs when a comet's solar elongation is too small for observation with IUE. Surprisingly, the ratio of these new multiplets to that at 1814 Å is inconsistent by a factor of 5 with a straightforward fluorescent pumping mechanism using solar emission lines. Although anomalies in the relative strengths of the triplet components at λ1814 suggest that optical depth may be significant in that multiplet (Feldman, private communication), these newer results may require a complete reinvestigation of the fluorescent efficiences of all the S I multiplets. This could increase the total amount of S by a factor of 5 and thus remove one of the difficulties cited above with respect to a high abundance of SO.

A potentially important identification would be of OD since the ratio OD/OH is characteristic of the formation process of the icy grains. The most sensitive search thus far published is only an upper limit $[OD/OH] \lesssim 4 \times 10^{-4}$ (Ref 14), consistent with the upper bound from in situ measurements by Giotto (Ref. 15). A more sensitive search will be an imporant future task.

4. RELATIVE ABUNDANCES

Observations of species easily measured in the optical have shown no systematic difference in the composition of new and old comets (Refs. 16-18) even though very different photometric behavior is a well established characteristic (see below). The same optical observations have shown that, with remarkably few exceptions, the total scatter in relative abundances from comet to comet is little more than a factor of 2, i.e. only slightly larger than the uncertainties inherent in most of the data except for some comets noted below. The only compositional parameter known to vary dramatically from one comet to another is the gas-to-dust ratio but this is not correlated with the dynamical age of the comet using either optical data (Ref. 19) or data from IUE (Ref. 20). One might expect to find compositional differences in the ultraviolet where quite different species are observable. However, as originally pointed out by Weaver et al. (Ref. 21) and noted further in previous reviews (Refs. 1,2), the relative abundances determined

with IUE in most cometary comae seemed remarkably uniform but no dynamically new comet had ever been observed in detail or with sufficient sensitivity with IUE until Comet Wilson in 1986-87. The two other dynamically new comets (Bowell 1982 I, Cernis 1983 XII) observed with IUE had perihelion distances beyond 3 AU and were therefore observed only close to perihelion when very long exposures were barely sufficient to show the very strong 0-0 band of OH.

The interesting abundances, of course, are those of the parent molecules in the nucleus since it is these abundances which will tell us about the formation of comets. If the abundances are uniform from comet to comet and with depth in the cometary nucleus, one can argue for homogeneous accretion in a uniform (or at least well mixed) region of the solar nebula. Variations from comet to comet or between new and old comets can tell us respectively about spatial variations in the nebula and about temporal variations during the accretion stage. These abundances must be inferred from measurements of column densities in the coma. This naturally requires a good knowledge of the physical processes involved, something we are skipping over in this review. For some easily observed species, such as OH and CS, a single parent molecule (likely H_2O and CS_2 respectively) is likely to produce all molecules of the observed species and the spatial distribution has been measured either with IUE or with other instrumentation so that one can make reasonable inferences about the ejection of the parent molecules based on a measurement of the column density of the fragment. For these species, therefore, one can ask how the production rate varies with heliocentric distance or from one comet to another. For other species, such as CO_2^+, it is much more difficult to interpret a column density of the observed species in terms of the production of its parent (presumably CO_2). As a result, one can realistically compare one comet with another only by choosing comets observed with similar geometries, i.e. at similar geocentric and heliocentric distances. Fortunately, there now exists a sufficient ensemble of cometary observations that one can often find such a comparison for any given observation and thereby bootstrap one's way to many comets. When looking at atomic abundances the same problems are compounded because most atomic species have multiple parents and, except for H, the spatial distributions are not well studied. For this reason it is best to compare atomic abundances in the same way one does CO_2^+, i.e. by comparing comets observed at comparable geocentric and heliocentric distances. The easily observed $L\alpha$ line is not normally used to determine the column density of H because it is optically thick and a single measurement on the nucleus is not easily interpretable. Models exist (Refs. 22, 23) for interpreting these data if the spatial distribution is measured but such data are better obtained from rockets and other spacecraft with imaging or scanning systems (e.g. Pioneer Venus Orbiter) than with IUE.

4.1 New Comets Vs. Old Comets

With the advent of Comet Wilson 1986ℓ, Roettger et al. (Ref. 13) have finally succeded in using ultraviolet data to address the question of relative abundances in a new comet in comparison with those in old comets. Fortunately, P/Halley 1986 II was observed before perihelion at geocentric and heliocentric distances comparable to those of C/Wilson near perihelion. Furthermore, the production rates of OH were nearly the same in the two comets at these times so that the effects of density-dependent chemical processes in the coma should be similar for both comets and any differences in column densities must be attributable to differences in nuclear composition. Table 2 excerpts some of the key results from Ref. 13.

Table 2.

Abundances in a New and an Old Comet

		P/Halley 1985/12/16 pre-perihelion	C/Wilson 1987/4/11 pre-perihelion	C/Wilson 1987/4/22 post-perihelion
r	[AU]	1.24	1.21	1.20
Δ	[AU]	0.85	0.99	0.71
N(OH)	$[10^{12}cm^{-2}]$	134	130	136
N(CS)	"	2.0	1.2	1.5
$N(CO_2^+)$	"	7.7	8.2	10.2
N(CO)	"	<150	<84	<96
N(CI)	"	9.5	4.0	3.7
N(O I)	"	48.8	37.6	51.9
N(S I)	"			
(λ1814)		7.5	3.4	3.9
(λ 1474)		<85	17	25
$Q(H_2O)$	$[10^{27}s^{-1}]$	246	235	230
$Q(CS_2)$	"	0.19	0.14	0.12

From: Roettger et al. (Ref. 13)

Examination of those numbers shows that most species have virtually identical abundances in both comets providing a perhaps surprising confirmation of the similar conclusion regarding optically observed species. The only exceptions are that C and S are both underabundant by roughly a factor 2 in the new C/Wilson relative to the old P/Halley and even these differences are barely pushing the limits of the scatter among optically determined abundances. All of the measureable parents of these species, however, have abundances similar to those in Halley thus emphasizing the difficulty of interpreting the atomic abundances. Although no explanation has been suggested for the difference in column density of S other than an unknown parent (CS differs much less between the two comets), it is plausible to suggest with Roettger et al. (Ref. 13) that the difference in the column density of C is due to a difference in the abundance of CO which is known to be the second most abundant volatile in P/Halley (Refs. 24, 25). Although CO was undetectable in C/Wilson at any time and in P/Halley at the time the geometrical circumstances matched those of C/Wilson, it was readily detectable with IUE when P/Halley was closer to perihelion (see Figure 1) and the relative abundance at that time is consistent with all the upper limits for both P/Halley and C/Wilson in Table 2. Optical data on the forbidden lines of [O I] have been used to infer significant variations in the relative abundance of CO or CO_2 from comet to comet (Ref. 26) but the required confirmation with direct observation of CO in numerous comets in the ultraviolet must await

either a breakthrough in extracting weak signals from IUE spectra or a spacecraft with the next generation of instrumentation.

4.2 Two Anomalous Comets

There are two comets observed with IUE, out of a total of 32 comets, which show significant compositional anomalies - P/Encke and P/Giacobini-Zinner. These two comets also show significant compositional anomalies in the optically observed species and they are the only two comets for which major compositional anomalies have been quantitatively well documented at relatively small heliocentric distances (see Ref. 27 for anomalies at larger distances). It should be remembered that most species observed either with IUE or in the optical are trace species compared to OH, H, C, and O. All other species readily observed imply abundances of their parents in the nucleus less than 1% that of H_2O. Only CO is known to have an abundance which is significant and because its g-factor (fluorescence efficiency) is so low it is observable only under optimum circumstances in bright comets.

Comet P/Giacobini-Zinner, the first comet visited by a spacecraft, has been known for decades to exhibit anomalous relative abundances of the optically observable trace species. During the last apparition, abundances were first determined relative to OH in both the optical and the ultraviolet providing the normalization necessary to interpret the anomaly. In the optical CN has a normal abundance while NH, C_2, and C_3 are depleted by roughly an order of magnitude (Refs. 28, 29). A spectrum taken with IUE is shown in Figure 4 (Ref. 41). A comparison with Figure 1 suggests that the relative abundance of CS is "normal" and a quantitative analysis confirms that it is. The abundance of NH, however, is strongly depleted relative to OH even after taking into account the poor signal-to-noise ratio at the wavelength of the NH band and variations in the g-factor for OH. The NH band is undetectable in P/Giacobini-Zinner (Fig. 4)

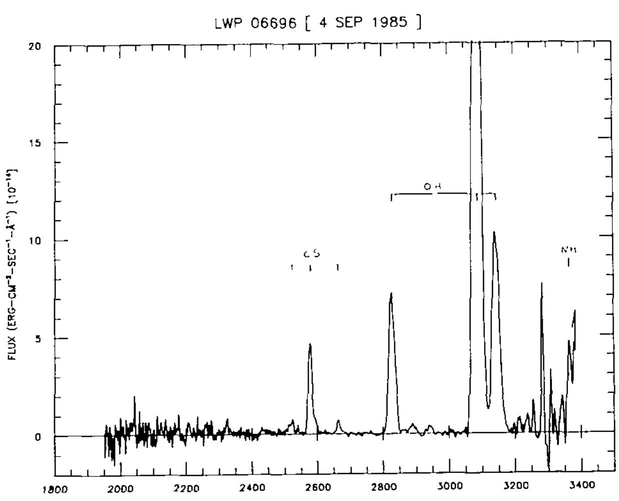

Figure 4. Spectrum of P/Giacobini-Zinner on 1985 September 4. Note that the strength of the 0-0 band of CS is comparable to that of the 1-0 band of OH whereas the 0-0 band of NH is undetectable and certainly far weaker than that of CS. In P/Halley (Fig. 1) and most comets, NH is stronger than CS.

whereas it is stronger than that of CS in P/Halley (Fig. 1). If it were not for this depletion of NH, one would be tempted to attribute the anomalies to depletion of carbon polymers in the nucleus but not of other carbon compounds. With the strong depletion of NH, however, the nature of the depletion in the nucleus is unclear and, as yet, uninterpreted. Whether this implies formation of this cometary nucleus in a different part of space than most cometary nuclei or is an evolutionary effect is not yet known.

The anomalies in P/Encke are even more unusual than those in P/Giacobini-Zinner since the relative abundances are normal preperihelion and anomalous post perihelion. In this case, furthermore, all trace species are depleted relative to OH. Figure 5 shows IUE spectra of P/Encke before and afer perihelion at similar heliocentric distances and the difference in the relative strength of CS and OH is dramatic. Although some of this difference is due to differing g-factors and to differing geometries, the production of the parent of CS is down by a factor of 4 postperihelion (Ref. 30) as are most optically observed trace species. Sekanina (Ref. 31) has modelled the

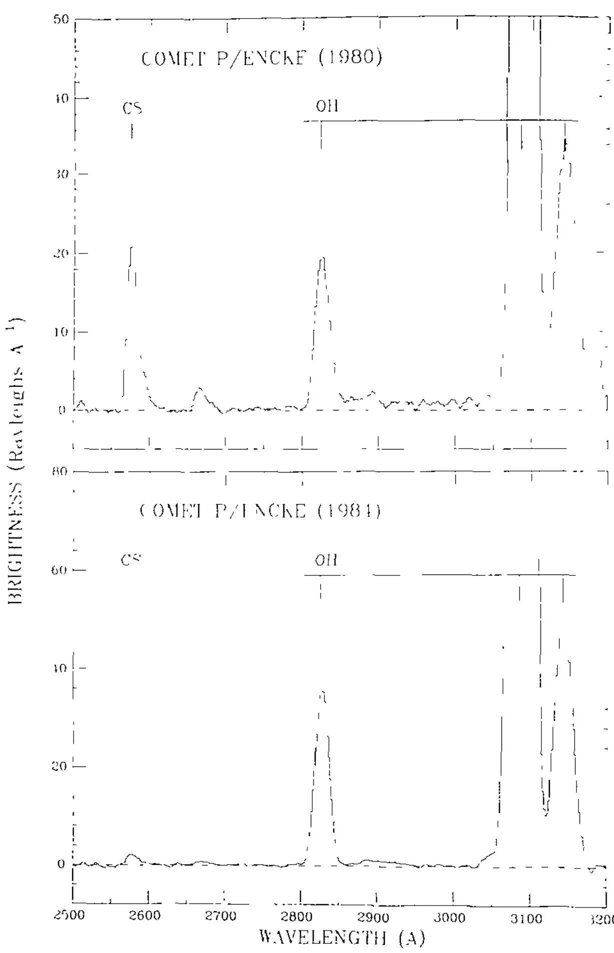

Figure 5. Spectra of P/Encke at comparable heliocentric distances before (upper panel) and after (lower panel) perihelion. The difference in the relative strength of CS is dramatic. Although part of the difference is due to differing geometry and g-factors, there is a difference in rleative production of CS by at least a factor 4.

nucleus of P/Encke and concluded that the emission at the two times corresponding to Figure 4 is from two quite different active areas on the nucleus, one near the north pole of the nucleus preperihelion and one near the south pole postperihelion. Why these two areas should exhibit such different compositions, however, is not understood. We note that P/Encke might well be the most highly evolved comet known since it has undergone more observed passages close to the sun than any other. This evolution is known to have affected the two hemispheres differently so that anomalous abundances may be an effect of mantle formation rather than a primordial heterogeneity in the nucleus. This question has thus far not been addressed.

Although these two comets are dramatically different from others, I would like to stress that they are rather rare exceptions to the pattern. Most comets exhibit very similar compositions as measured with IUE. The challenge is to find other species which can be measured in a large number of comets with CO being the most tantalizing possibility both because of its high abundance in P/Halley and because of the indirect evidence that it may vary significantly from comet to comet.

5. VARIABILITY OF COMETS

Two types of variability are important in understanding the behavior of comets - the overall variation with heliocentric distance and shorter-term variations. Both types of variation can tell us about the cometary nucleus. The overall variation can tell us about the volatility of the ice which controls the vaporization, e.g. whether the dominant ice is water or a more volatile species such as CO, and about the existence and blow-off of refractory mantles. The shorter term variation can tell us about cometary rotation, the homogeneity of the surface, and the degree of coverage by a mantle. Observations with IUE are particularly valuable because the OH bands monitor the production of water vapor, the species that is known to be the most abundant volatile in P/Halley and thought to be the most abundant in most comets.

5.1 Variation with Heliocentric Distance

Most comets observed with IUE have shown a fairly steep variation in the production of OH as a function of heliocentric distance inside 2 AU. Figures 6, 7, and 8 show three examples. C/Bradfield 1979 X was the first comet whose variation with heliocentric distance was studied with IUE (Ref. 32). In the range $.5 < r_H < 1.5$ AU, the variation in production of water is reasonably smooth, varying as $r^{-3.7}$, as the comet receded (the comet was not observable before perihelion). P/Giacobini-Zinner was observed over a rather small range of heliocentric distance although the range of time was three months (Ref. 33). It too varied smoothly and steeply but with the peak outgassing occurring a full month before perihelion. P/Halley was seen to vary steeply for heliocentric distances beyond 1.5 AU but relatively slowly at smaller distances (Ref. 24). P/Halley could not be observed with IUE near perihelion but for distances beyond 1 AU the comet was outgassing much more rapidly after perihelion than before.

The production of solid grains can be characterized by the quantity Afρ which is directly proportional to the production of solids as long as outflow velocity of the solids, scattering

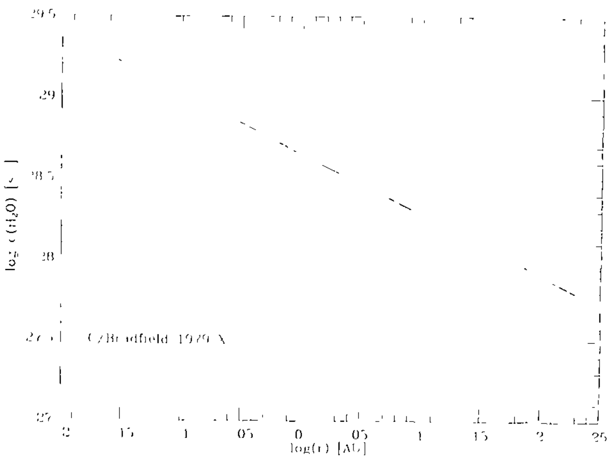

Figure 6. Production of water by C/Bradfield 1979X. A Straight line through all but the last point corresponds to variation as $r^{-3.7}$

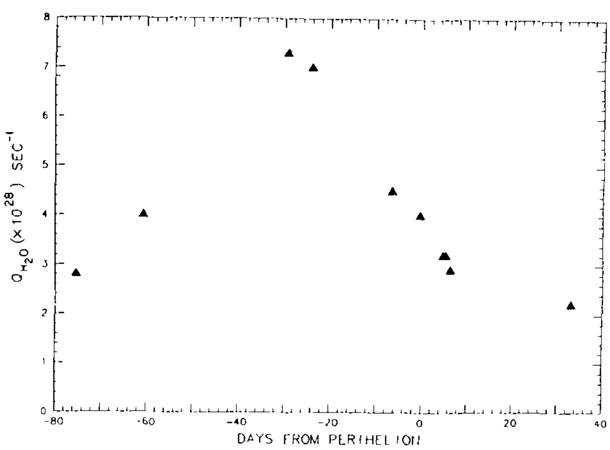

Figure 7. Production of water by P/Giacobini-Zinner 1985 XIII. Note the sharply peaked variation centered at a point roughly one month before perihelion followed by nearly constant prodution 1 to 2 months after perihelion.

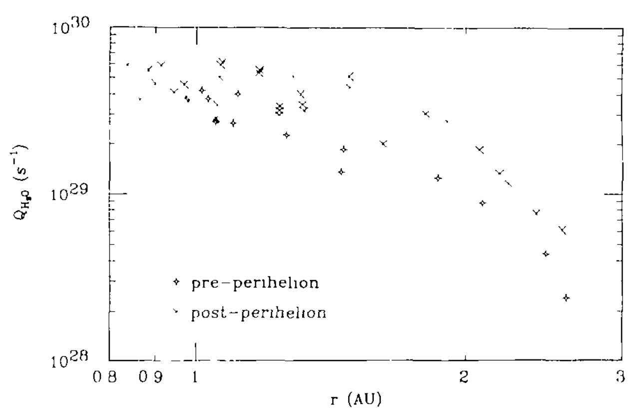

Figure 8. Production of water by P/Halley 1986 III. Note that the production is systematically higher after perihelion than before.

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properties, etc. remain constant. Although there appear to be significant variations in the ratio of gases to solids with heliocentric distance (Ref. 20), the production of dust is like that of water in varying steeply with heliocentric distance at least for some distances inside 2 AU although, unlike that of water, the production of dust in P/Halley continued to increase inside 1 AU as shown in Figure 9 (Ref. 20).

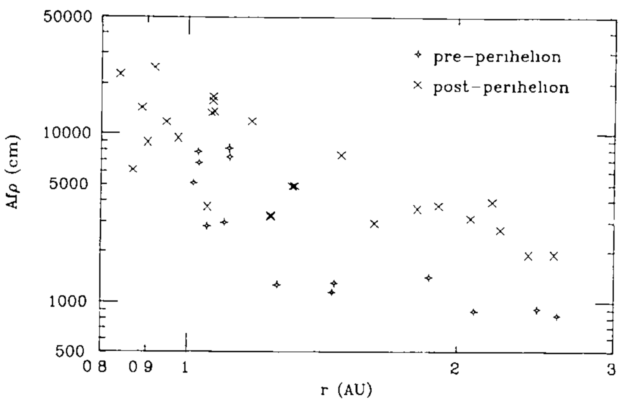

Figure 9. Production of solid grains by P/Halley as measured by the parameter Afρ. This is proportional to the production rate if scattering properties and outflow velocity remain constant.

These results can probably be generalized to the ensemble of comets, other than new comets, on the basis of visual magnitudes. They suggest that nearly all short- and long-period comets vary steeply in brightness, and therefore presumably in vaporization of water, inside 2 AU. They also suggest that asymmetries about perihelion are common and that the comets are comparably likely to be brighter before perihelion or after. The results from IUE imply that the outgassing of water behaves in this same manner and probably controls vaporization in all these comets. All of the above behaviors can, at least qualitatively, be understood as a combination of vaporization controlled by water, seasonal variation due to obliquity of the polar axis, shielding/heating by dust in the coma, and mantle coverage of a significant fraction of the surface.

The behavior of new C/Wilson was totally different. Figures 10 and 11 show the variation in the production of water and of solid grains in C/Wilson (Ref. 13). The release of water varied steeply as the comet first approached 2 AU but no faster than r^{-1} inside that distance, and it actually decreased smoothly as the comet approached perihelion (1.2 AU). The vaporization of water was systematically lower after perihelion. Beyond 3 AU, C/Wilson was an order of magnitude more active than an extrapolation of the curve for P/Halley. The behavior of the dust was even more extreme since the production decreased almost monotonically from outside 3 AU through perihelion. It is interesting to note that new comets Bowell (Ref. 34) and Cernis were also both observed near perihelion near 3 AU and were also found to be emitting signficant OH. It has been widely observed that dynamically new comets have unusually shallow visible light curves on first approach to the inner solar system (Ref. 35) having brightened sharply at large distances. This has been interpreted as being due to the vaporization of the outermost layer of the nucleus that has been made more volatile by irradiation with

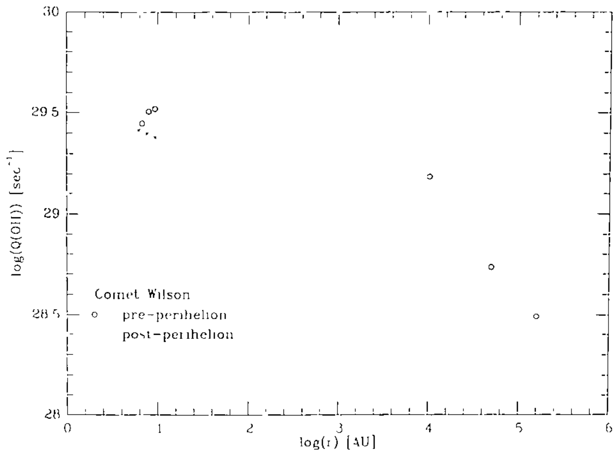

Figure 10. Production of water by C/Wilson 1986 I. The slope preperihelion inside 2.5 AU must average no more than r^{-1}. Note that the comet is systematically fainter after periheon.

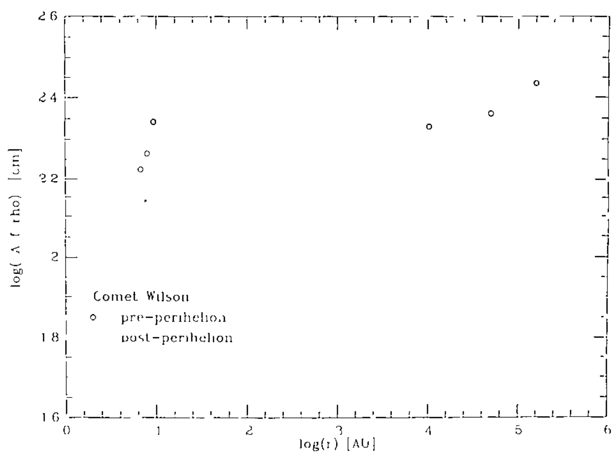

Figure 11. Production of dust by C/Wilson 1986 I. Note that this decreases monotonically as the comet approaches the sun.

cosmic rays during 4.5 billion years in the Oort cloud (Ref. 36-38). The clear extension of that interpretation is that many of the grains released at large distances are large, icy grains which begin to evaporate when the comet reaches 4 to 5 AU. These grains then provide a significant fraction of the OH seen in new comets at that distance and their vaporization also explains the apparent decrease in production of grains. Once the comet reaches about 3 AU, the vaporization of the nucleus again becomes significant both adding to the OH and increasing the apparent production of grains. The new comets then behave like more typical comets when receding from the Sun. This general scenario explains most of the data. Detailed models of C/Wilson have not yet been constructed to test the picture quantitatively. Explaining the difference between the behavior of new comets and old comets is likely to be the key in understanding the irradiation of comets in the Oort cloud.

5.2 Short-Term Variability

One of the dramatic results from the observing program on P/Halley was the short-term variability with very large amplitude. Since P/Halley was

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studied so much more intensively than any other comet, one might ask whether this variability was seen only because we looked harder or whether it is a common phenomenon, whether it is limited to certain heliocentric distances, and whether it is limited to old comets or occurs in new comets also. With the limited statistics of only one new comet observed with IUE, it is impossible to answer this question based solely on the data from IUE.

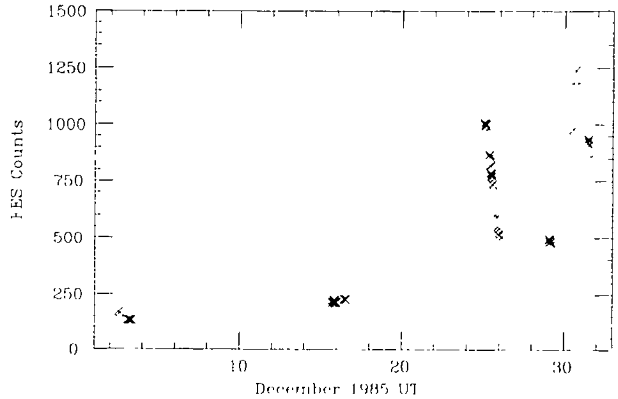

Figure 12. Light curve of P/Halley in December 1985 as measured with the FES. Note the onset of large-amplitude variability in mid-December.

Figure 12 shows the onset of the variability as measured with the FES in P/Halley between 1.25 and 1.1 AU. One of the free extras with IUE is a broad-band visible photometer which is free of atmospheric effects and therefore able to provide long-term monitoring of brightness. Since the tracking of the spacecraft is checked frequently when observing comets, we get frequent measurements of the brightness which yield a light curve such as that in Figure 12. It is clear that there was a dramatic change in P/Halley's behavior in mid-December since prior to that time FES counts during a shift always remained relatively stable during a shift, like the observations on the left half of the figure, whereas from mid-December until June of 1986 there was a significant variabilty, like that in the right half of Figure 12, in the FES counts during each shift. The spectrometers on IUE do not provide such good temporal resolution but the variability of Halley was still obvious in the spectra. Figure 13 shows the production of H_2O and CS by Halley when it first satisified the pointing constraints of IUE after perihelion (Ref. 39). Variations by a factor 3 from day to day are clear. Similar variability has been observed at 1 AU in some other old comets, such as IRAS-Araki-Alcock 1983 VI (Ref. 10), but other old comets have been observed to be very steady at 1 AU, such as P/Giacobini-Zinner (Ref. 33). Prior to IRAS-Araki-Alcock, cometary observers had not realized the value of the FES in monitoring the comet but there are suggestions of short term variability in the gaseous production rates of C/Austin 1982 VI shown in Figure 14 (Ref. 40). The deviations from a smooth variability with heliocentric distance may be indicative of short-term variability although they need not be due to this. I infer that short term variability is common but not universal among old comets. The plausible interpretation in the case of P/Halley is that the variabilty set in when one of the active areas, photographed subsequently with the Vega and Giotto spacecraft, broke through a mantle of non-volatile material. Whether this process is characteristic of old comets remains to be seen.

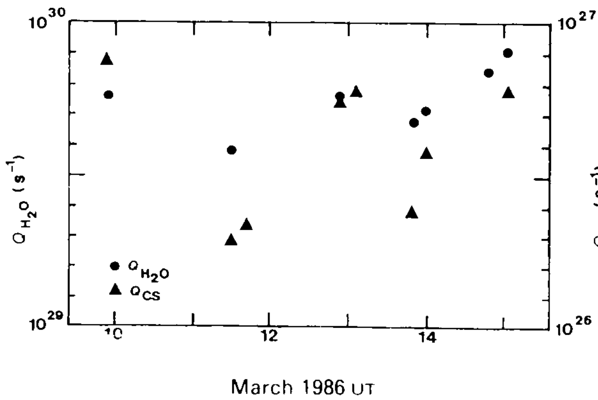

Figure 13. Variability of water production by P/Halley in March 1986. Although this does not have the temporal resolution of the FES data, it is clear that the vaporization varied by a factor of a few from day to day.

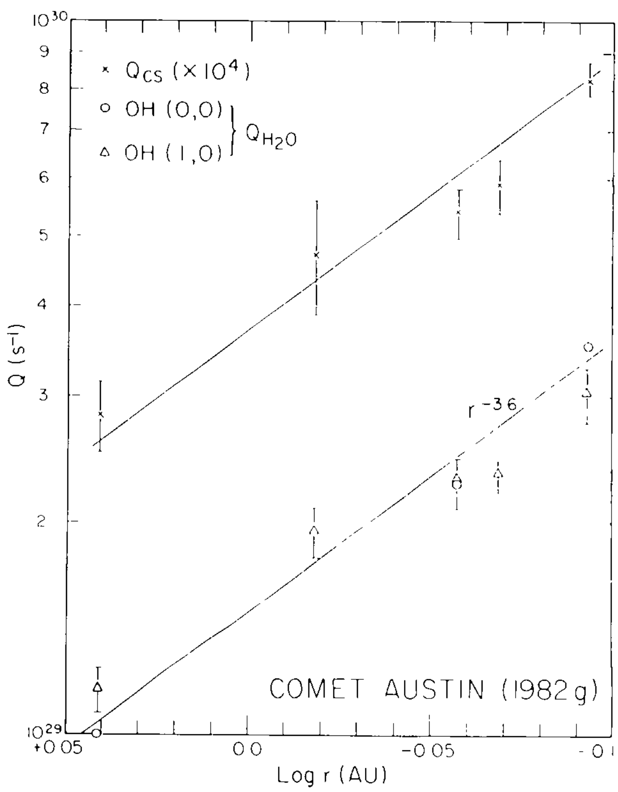

Figure 14. Variation of water production by C/Austin 1982 VI as a function of heliocentric distance. The significant variations around a smooth curve may be indicative of short-term variability as in P/Halley.

C/Wilson, on the other hand, exhibited absolutely no short-term variability. The variation of production rates varied smoothly with heliocentric distance (see Figures 10 and 11 above) and the FES varied negligibly over long periods as shown in Figure 15. Over 24 hours on April 3-4 the FES varied by less than 5%. This behavior persisted over the entire apparition. Unfortunately we do not know if this behavior is due to the fact that the comet is a new one or due to the fact that it did not approach quite close enough to the Sun to

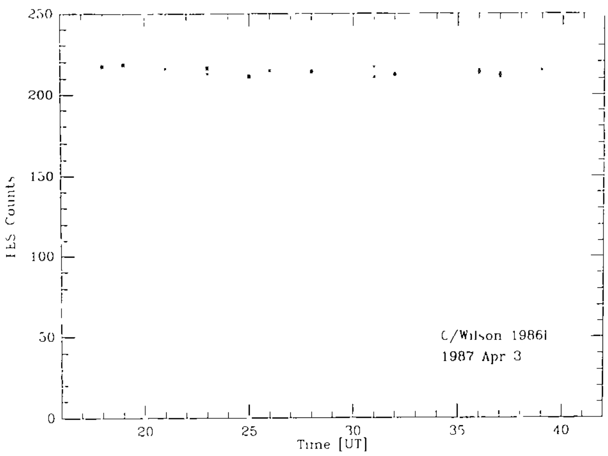

Figure 15. FES light curve of C/Wilson 1986I for 24 hours in April 1987. The visible light is constant to within 5% over this period.

trigger the short-period variations. Certainly comet Kohoutek 1973 XII, another dynamically new comet observed with many techniques, showed many signs of short term variability after it was inside 1 AU but it was not well enough observed before passing inside 1 AU to know whether variability was present at distances comparable to those of C/Wilson.

It is possible that a new comet must pass close to the Sun (say 0.5 AU) in order to form a significant mantle whereas several passes at larger distances form enough of a mantle that long-period and short-period comets can exhibit outbursts at larger distances from the Sun. In the absence of data on more dynamically new comets, however, this is pure speculation.

6. COMETARY MASSES

One of the most fundamental properties of any celestial body is its mass - a property that has never been measured, except in model dependent ways, for any comet. In the case of a comet, the more interesting property is the mean density which could be determined if mass and radius were known since the density will constrain the accretion process by which the comets formed. Although upper limits to cometary masses have been determined from the absence of gravitational interactions, the closest we have come to the measurement of a mass is by modelling the nongravitational acceleration which is produced by the rocket-like ejection of gas preferentially from the hottest part of the surface, i.e. at the part of the surface in local "afternoon" (Ref. 41).

Data from IUE have now been used to measure the velocity of the OH in P/Encke with unprecedented accuracy, to better than 1 km/sec, by using the Greenstein effect, the variation in relative line stengths due to differing heliocentric radial velocities within the cometary coma. Unlike a direct measurement of the Doppler shift, this method requires only that the wavelength of an emission line be determined accurately enough to uniquely identify the line but it does require a photometric calibration. Although the method is not generally applicable, it is applicable to any source shining by fluorescence pumped by a source with strong absorption or emission lines at the wavelengths of interest. The effect is seen in

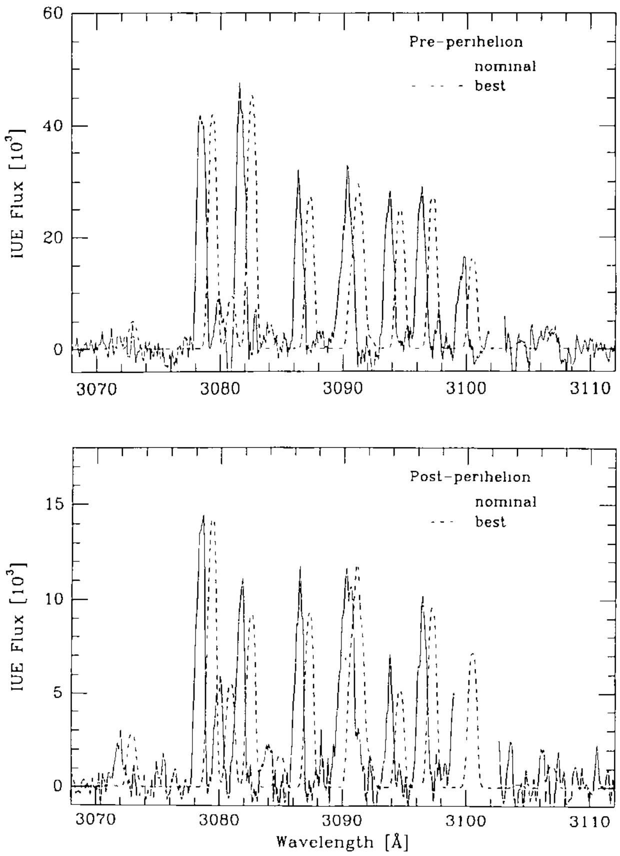

Figure 16. Observed and theoretical spectra of OH in P/Encke before and after perihelion. The dotted curve is computed for the radial velocity of P/Encke's nucleus (and offset in wavelength for clarity) while the dashed curve is computed for the 'best-fitting' velocity. In the preperihelion spectrum the offset is 1.6 km/sec and the agreement of the relative intensities of the lines is remarkably improved.

comets not only in the bands of OH but even in the atomic lines, such as O I λ1304.

Figure 16 shows two spectra of P/Encke, one before perihelion and one afer, both near r = 0.8 AU. The dashed lines represent theoretical spectra (offset in wavelength) at the nominal velocity of P/Encke's nucleus and offset to the "best fitting" velocity (Ref. 42). The pre-perihelion spectrum is fit far better with an offset velocity than with the nominal velocity. This offset velocity can be combined with the production of water determined from the brightness of the OH emission to yield the nongravitational force. A reanalysis of the nongravitational acceleration (assuming forces that vary with heliocentric distance in a way consistent with the latest data) will then lead directly to the mass of the nucleus. We have presented a preliminary analysis of these results but reanalysis of the orbital data has not yet been completed. Furthermore, the radius of P/Encke is not well determined so it is not yet possible to determine a density. It is not yet clear whether the nongravitational forces in other comets will be measureable since the ejection must be extremely anisotropic to produce a significant Greenstein effect. If the same nongravitational force is produced with a smaller anisotropy but a correspondingly larger rate of outgassing, it will

not be detectable with our present signal-to-noise ratio since the intensity ratios in the present spectra allow no better than ±0.5 km/sec.

This recent result, which is based on archival data from 1980, suggests that there may be many other new ways to use the IUE data to answer questions previously thought to be outside the capability of IUE. The use of the archival data will be limited only by the creativity of the users.

7. ACKNOWLEDGEMENTS

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